Deep Space Navigation

Innovation at Work

OUTLINE

* Introduction to the Navigation functions
* Improvement over the years - planned innovation
*

Donald L. Gray

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Navigation Functions

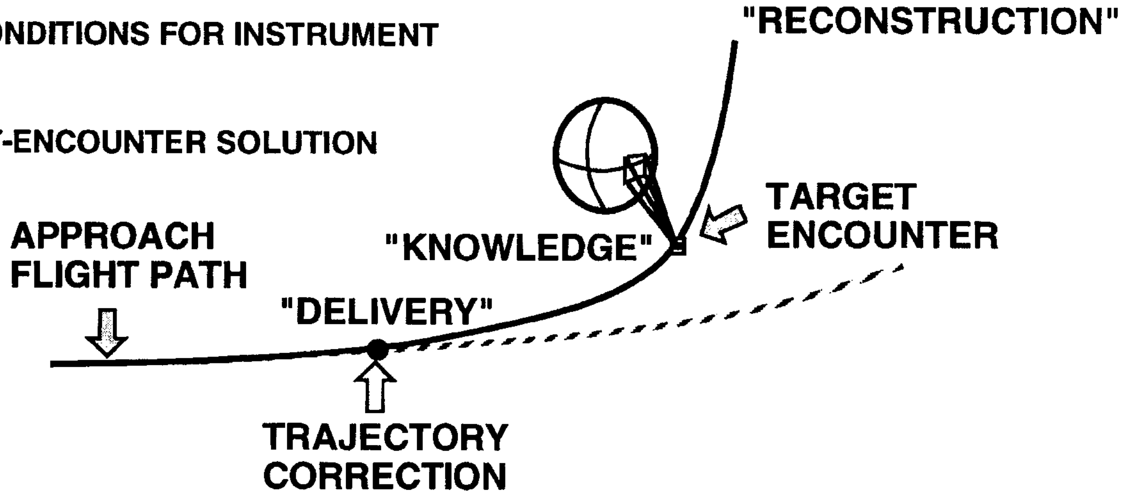
- **These five tasks need to be performed for successful navigation, be it on Earth or in interplanetary space:**

Task	Example on Earth (Hiking)	Example in Space
(1) **Obtain a Map**	Obtain road map, digital map database	Develop planetary ephemerides
(2) **Develop a Travel Plan**	Select trail(s) to reach destination estimate arrival time	Select orbit(s) to reach destination planet/asteroid, calculate arrival time
(3) **Take Meaningful Measurements**	Note time arrived at significant landmarks, note direction with a compass	Use radio signals and/or optical measurements to compute spacecraft position and velocity.
(4) **Calculate One's Position**	Compare actual arrival time at waypoint to predicted time	Estimate size, shape and orientation of orbit
(5) **Select a New Optimal Route**	Walk faster/slower, change direction	Change orbit using propulsion system

- **Tasks 1-2 are done pre-launch; others from launch to end of mission**

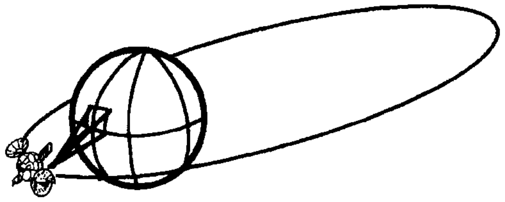
Navigation Objectives in Different Mission Phases

- **FLYBY/ORBIT INSERTION:**
  - DELIVER SPACECRAFT TO DESIRED LOCATION AT DESIRED TIME
  - PREDICT ENCOUNTER CONDITIONS FOR INSTRUMENT POINTING/SEQUENCING
  - OBTAIN ACCURATE POST-ENCOUNTER SOLUTION



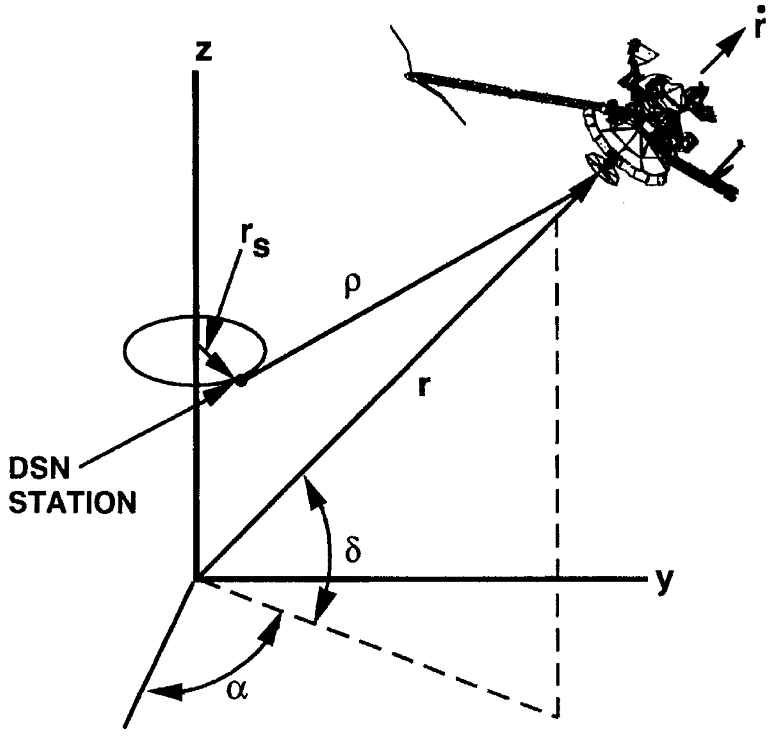
STEPS: MEASUREMENT ACQUISITION, ORBIT DETERMINATION, MANEUVER COMPUTATION AND COMMAND

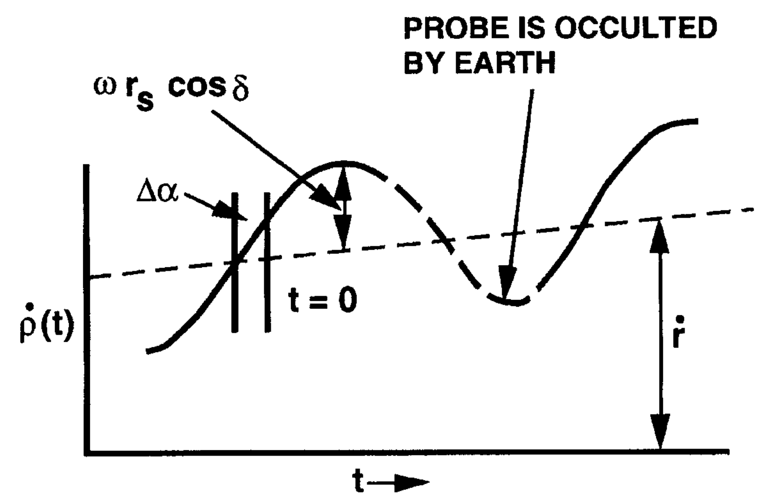
- **ORBITER:**
  - DETERMINE TRAJECTORY ON CONTINUING BASIS
  - MAINTAIN DESIRED ORBIT



Range and Doppler Tracking

- TWO-WAY RANGE AND DOPPLER DIRECTLY MEASURE LINE-OF-SIGHT COMPONENTS OF SPACECRAFT STATE
- DIURNAL SIGNATURE OF EARTH ROTATION ALSO PROVIDES ANGULAR STATE INFORMATION





$$\dot{\rho} = \dot{r} + (r_s \omega \cos\delta)\sin\omega(t - t_m) + \text{OBSERVATION ERROR}$$

WHERE t_m IS THE TIME OF MERIDIAN CROSSING

Voyager 2
Post Launch Receiver problem

- In supposedly quiet early cruise:
  - "Someone" forgot to send any message to Voyager 2 S/C for a week.
  - S/C programmed to switch receivers in case the prime one is not working.
  - Backup receiver did not work at all. After another week, S/C turned on the prime one again.
  - Difficulty establishing communication. Turns out the tracking loop capacitor was now apparently broken.
- Solution: Cancel most of the effect of Earths' rotation by a sequence of frequency ramps added to the uplink signal.
  - Multimission Navigation Group has been doing that ever since for Voyager 2.
  - Now so routine that they do it for all spacecraft.

Characteristics of Single-Station Doppler and Range Orbit Determination Capabilities

- Radial velocity derived from mean trend in Doppler data
- Radial position derived from mean trend in range data (or inferred from processing of Doppler data)
- Right ascension derived principally from phase of 24-hour signature in Doppler or range data
- Declination derived principally from amplitude of 24-hour signature in Doppler or range data -- poorly determined near zero declination

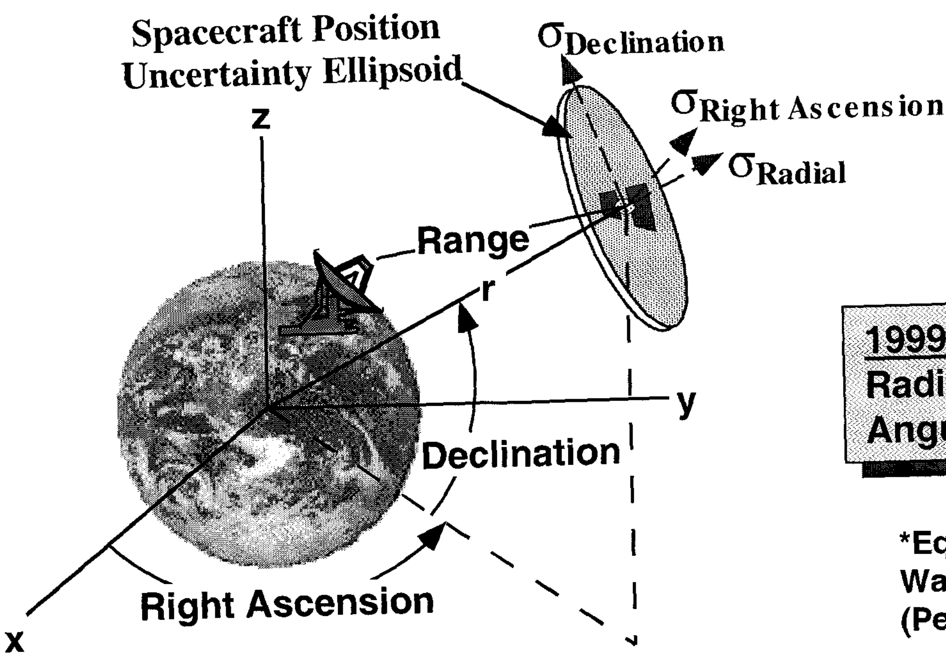
- Very accurate modeling of measurements and spacecraft dynamics is needed to infer quantities not measured directly -- angular position and rate components

Principal Error Sources in Radio Navigation

Error Source	Current Modeling Accuracy
Station Locations	
Crust-relative	5 cm
Pole location	5 cm
Timing (UTC)	0.5 ms
Media	
Ionosphere (X-Band, 8.4 GHz)	5 cm
Troposphere	4 cm
Ground Instrumentation	
Station oscillator	10^{-14}
Hardware range delays	0.5 - 1 m
Dynamics	
Nongravitational acceleration of spacecraft	10^{-12} - 10^{-11} km/s^2

Radio Metric Orbit Determination Accuracy -- Radial Versus Angular Components

- For most interplanetary missions, spacecraft position uncertainty is much smaller in Earth-spacecraft ("radial") direction than in any angular ("plane-of-sky") direction
  - Radial components of position and velocity are directly measured by range and Doppler observations
  - In absence of other data, angular components are much more difficult to determine -- they require either changes in geometry between observer and spacecraft or additional simultaneous observer, neither of which is logistically simple to accomplish
  - Angular errors are more than 1000 x radial errors even under the most favorable conditions (see below) when depending on range and Doppler measurements

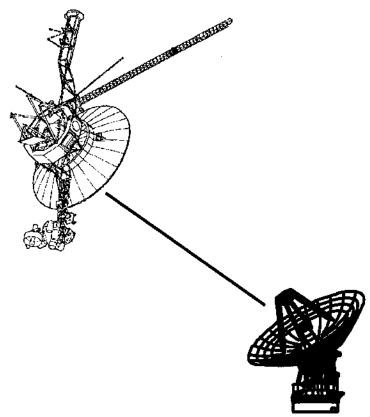


However: ΔDOR and NST data can directly measure these otherwise weaker angular components with varying accuracies

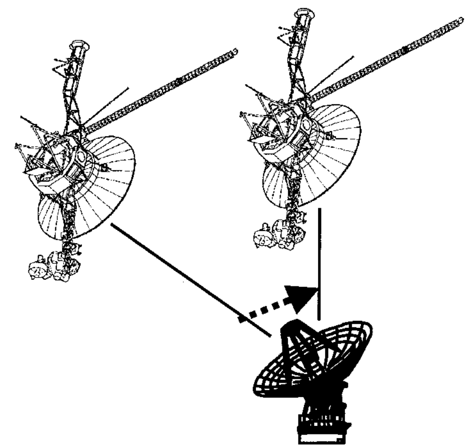
1999 Capability	Position	Velocity
Radial Error	2 m	0.1 mm/s
Angular Error (at 1 AU)	3 km*	0.1 m/s

*Equivalent to angle subtended by quarter atop Washington Monument as viewed from Chicago (Personally I prefer a silver dollar from Los Angeles)

Radio Metric Measurements -- Radial Data Types

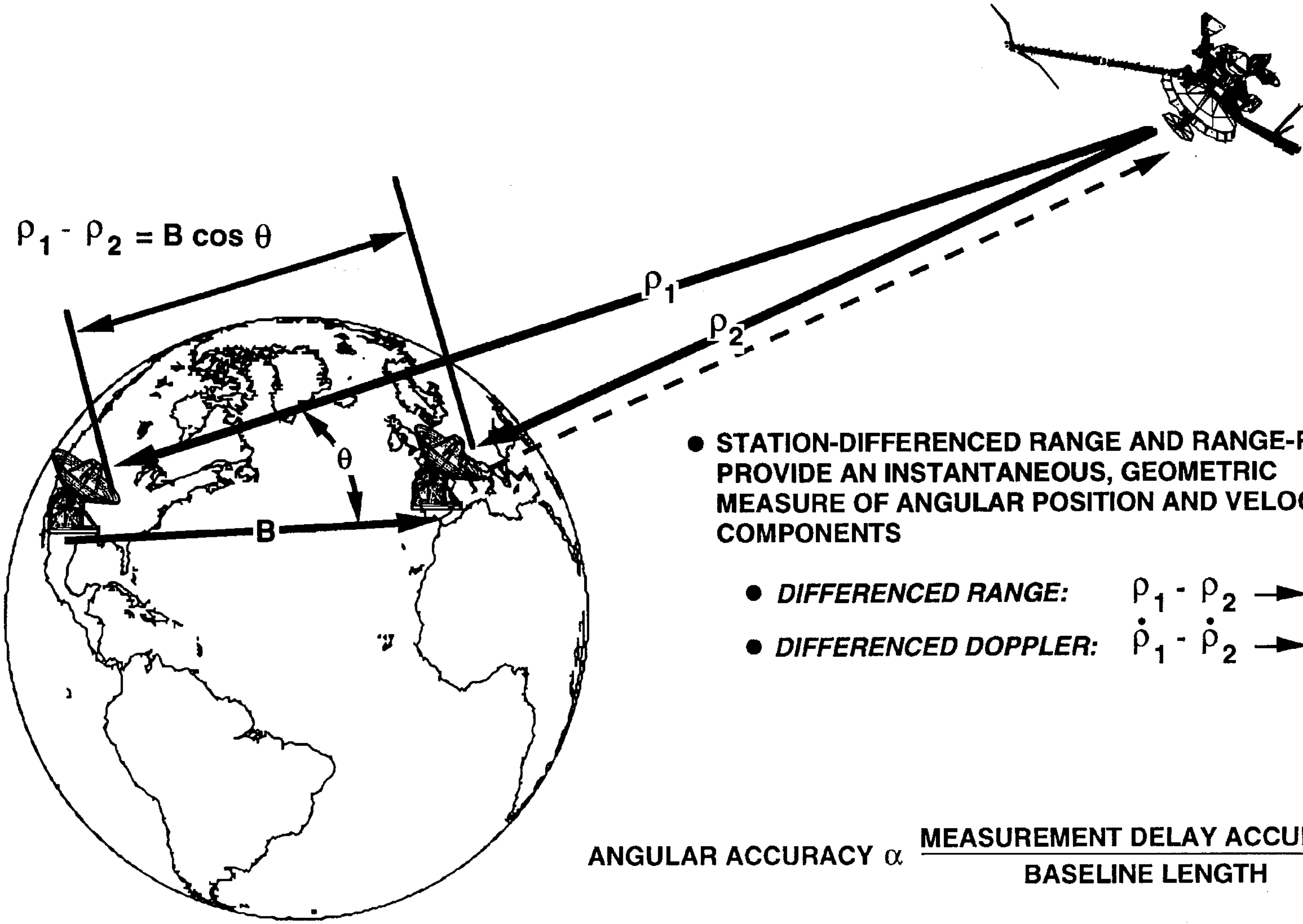


- Doppler
  - Measurements are comparisons of transmitted frequency (from ground station or spacecraft) with received frequency on ground; typical frequencies are at S-band (2 GHz) and X-band (7-8 GHz)
  - Useful for all mission phases
  - Highly reliable; used in all interplanetary missions to date
- Range
  - Measurements are typically two-way light time for radio signal to propagate between ground stations and spacecraft; typical frequencies are also at S- and X-band
  - Most useful during interplanetary cruise, planetary approach, and for surface positioning
  - Used in nearly all interplanetary missions since late 1960s



- Near Simultaneous Tracking
  - Two-way ranging between ground station and spacecraft, followed by additional ranging to second spacecraft in nearby part of sky in quick succession
  - Used to infer angular information if error sources are well-modeled; useful if one spacecraft is planetary orbiter and second is nearing that planet
  - Used between (1) Mars Pathfinder and MGS, (2) MGS and MCO, (3) MGS and MPL

Angular Tracking Using Station-Differenced Observables

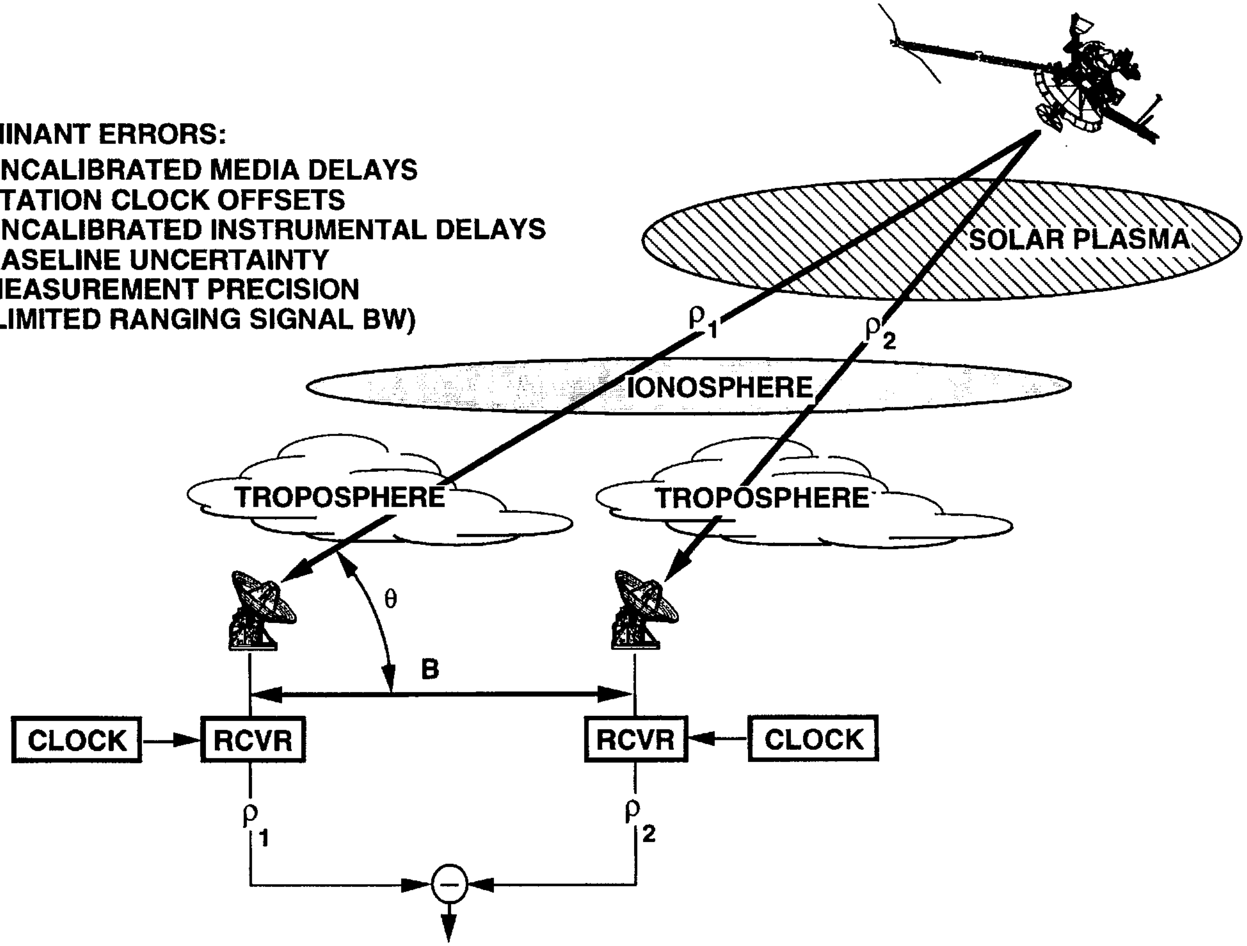


- STATION-DIFFERENCED RANGE AND RANGE-RATE PROVIDE AN INSTANTANEOUS, GEOMETRIC MEASURE OF ANGULAR POSITION AND VELOCITY COMPONENTS
  - *DIFFERENCED RANGE:* $\rho_1 - \rho_2 \rightarrow \theta$
  - *DIFFERENCED DOPPLER:* $\dot{\rho}_1 - \dot{\rho}_2 \rightarrow \dot{\theta}$

$$\text{ANGULAR ACCURACY } \alpha \ \frac{\text{MEASUREMENT DELAY ACCURACY}}{\text{BASELINE LENGTH}}$$

Differenced-Range Measurement Errors

- DOMINANT ERRORS:
  - UNCALIBRATED MEDIA DELAYS
  - STATION CLOCK OFFSETS
  - UNCALIBRATED INSTRUMENTAL DELAYS
  - BASELINE UNCERTAINTY
  - MEASUREMENT PRECISION (LIMITED RANGING SIGNAL BW)

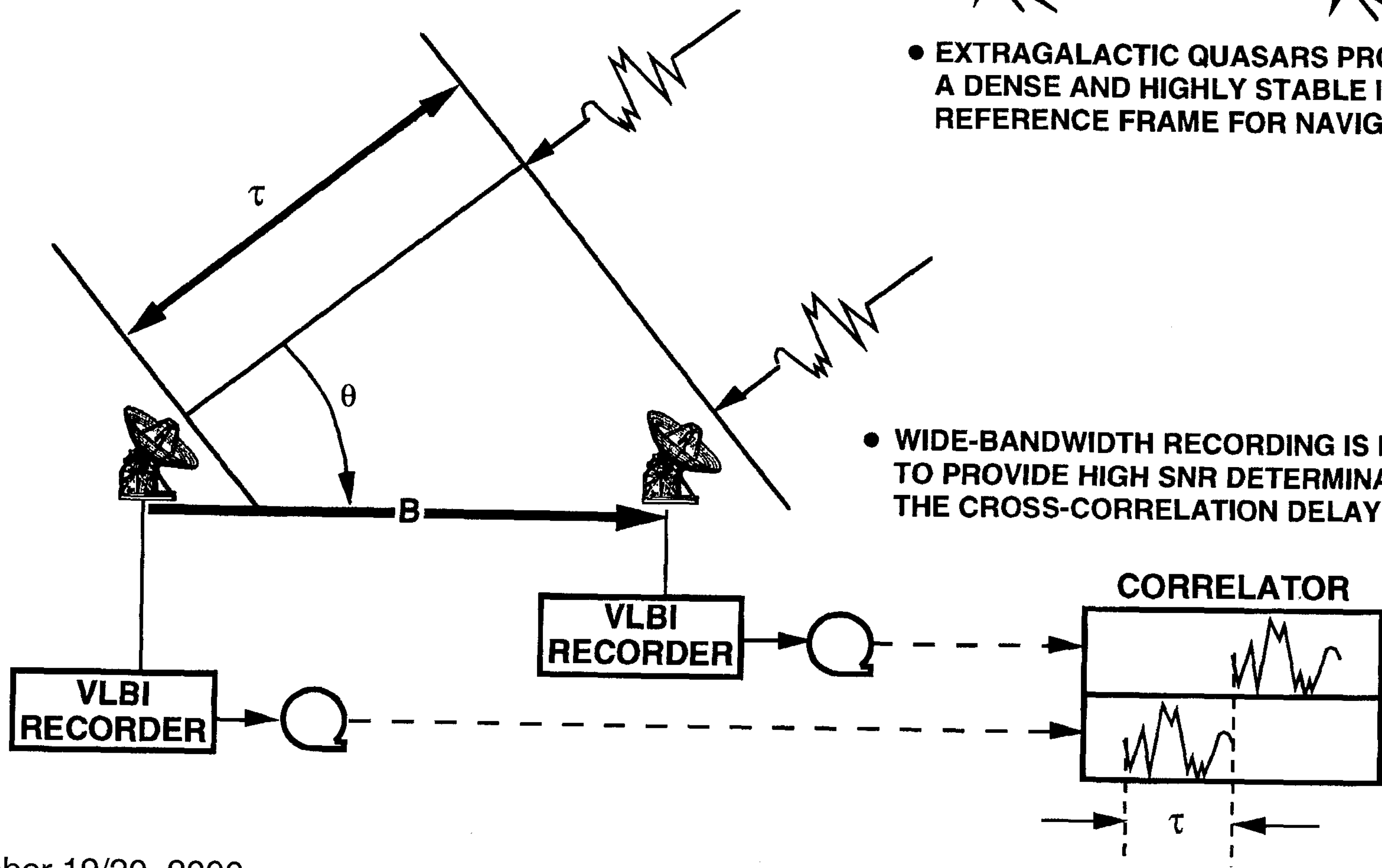


$$\rho_1 - \rho_2 = \mathbf{B}\cos\theta + c\,(\Delta\tau_{clock} + \Delta\tau_{inst} + \Delta\tau_{media}) + \mathrm{NOISE}$$

Very Long Baseline Interferometry

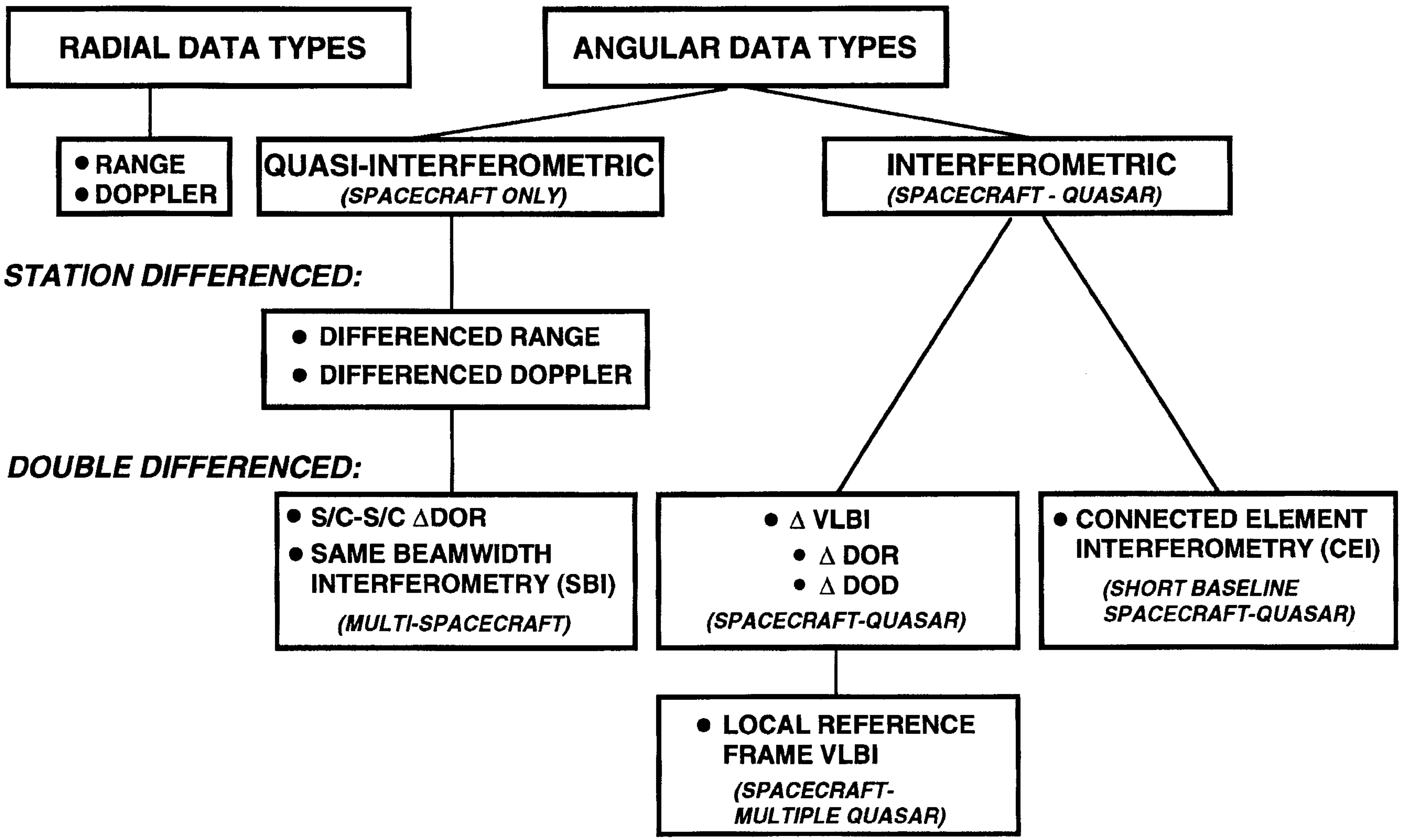
- VLBI ALLOWS DETERMINATION OF GEOMETRIC DELAY FOR NOISELIKE SOURCES BY CROSS-CORRELATING THE RECEIVED RADIO SIGNALS AT TWO STATIONS

- EXTRAGALACTIC QUASARS PROVIDE A DENSE AND HIGHLY STABLE INERTIAL REFERENCE FRAME FOR NAVIGATION



- WIDE-BANDWIDTH RECORDING IS REQUIRED TO PROVIDE HIGH SNR DETERMINATION OF THE CROSS-CORRELATION DELAY

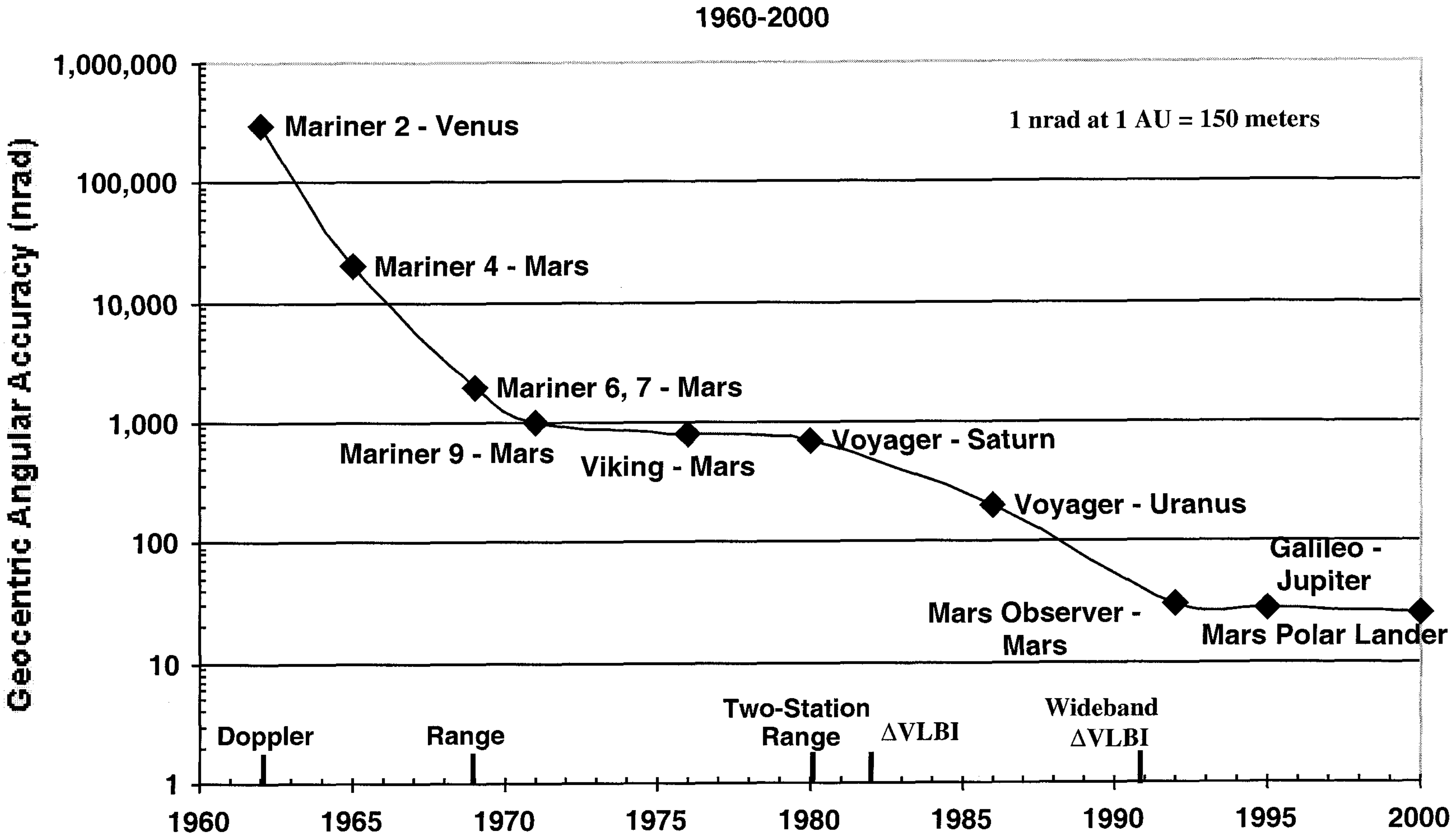
Earth-Based Radio Tracking Family Tree



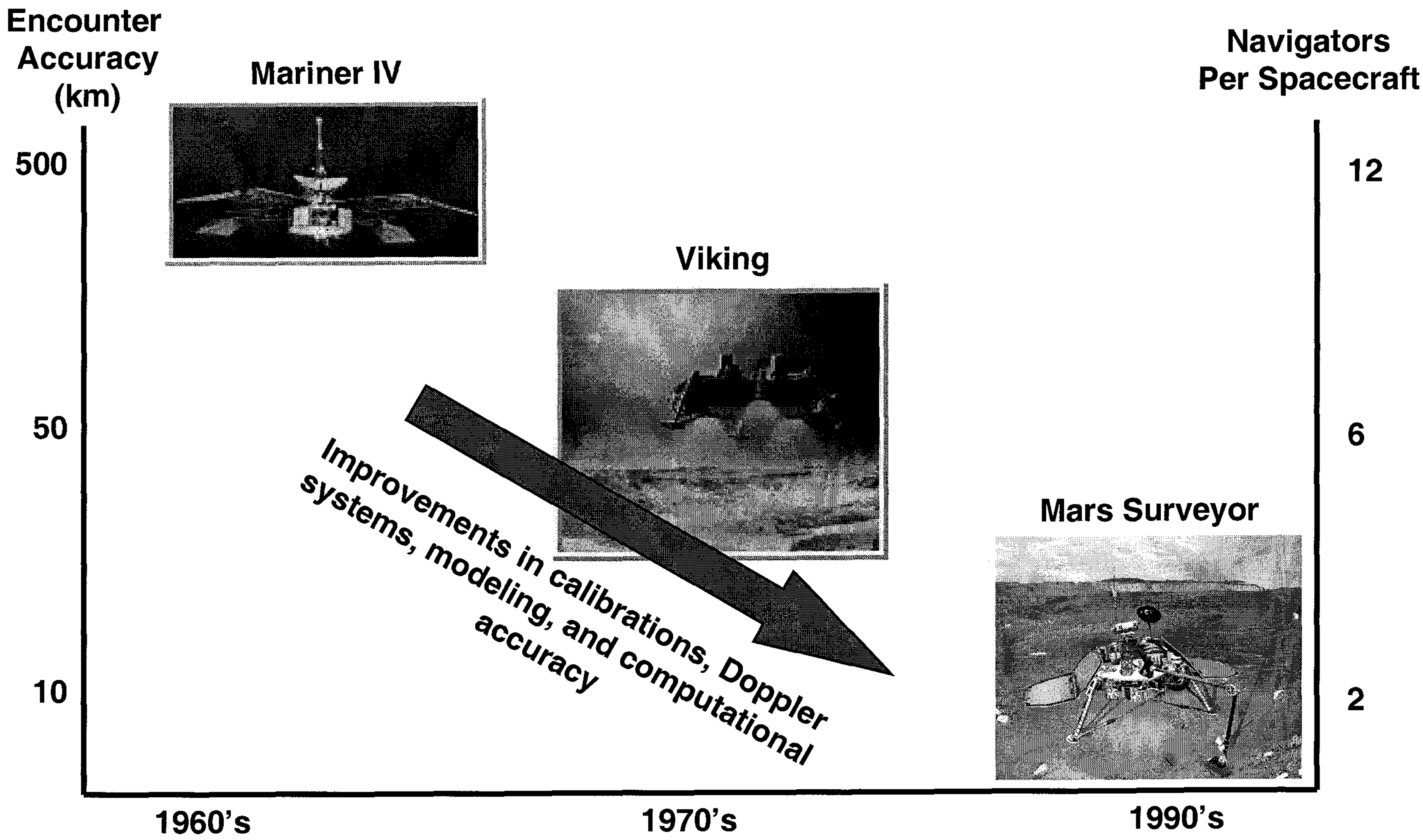
Optical Navigation Complements the Radio Capabilities

- On-board optical system takes pictures of reference bodies with respect to stars with known celestial locations
- These images are then used to compute angular positions of spacecraft with respect to reference bodies
- Objective diameter of imaging system limits resolution, due to diffraction; typical angular accuracy is 5 μrad
  - Rectilinear position error directly proportional to distance
    - 750 km at 1 AU
    - 5 km at 1,000,000 km
- Angular accuracy not as great as with radio metric data; however,
  - Angles are measured directly, rather than inferred through processing of line-of-sight data
  - **Angles are relative to target body, rather than Earth**
- Downtrack position not sensed until spacecraft-target geometry changes appreciably

Deep Space Navigation System:
Evolution of DSN Navigation System Accuracy



Benefits of Improved Radio Navigation Accuracy to Mars Missions



INNOVATIONS IN OPERATIONS

- **Timing of Maneuvers**
  - Used on Pioneer 10/11 to provide Earthline maneuvers w/great acc.
  - Used on Viking extended mission to provide period changes without needing turns. This conserved the remaining propellant.
  - P
- **Viking 2 Mars SOI - the pressure regulator starting leaking before the Mars Orbit Insertion. Rate of leak would have vented propellant. So we did an early maneuver to slow down the S/C. Only had about 1/2 the effectiveness of MOI, but better than losing the propellant.**

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  - L. Alberto Cangahuala
  - Leonard Efron
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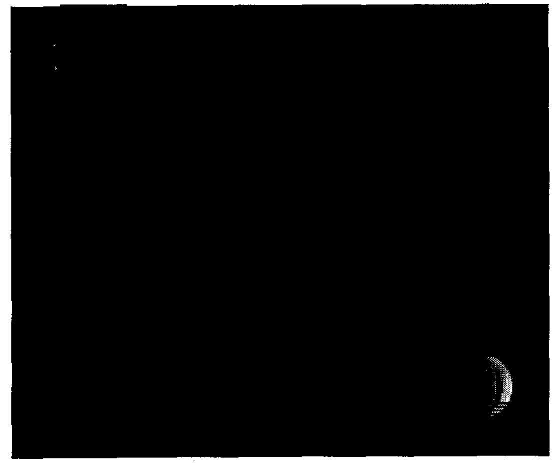
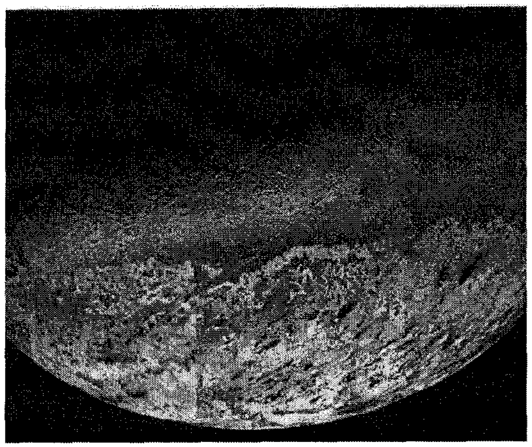
Benefit of Optical Navigation to Voyager Science



Sample OPNAV (Optical Navigation) Image

By taking distant optical navigation images such as this on Voyager, orbit determination accuracies improved dramatically,



Triton Mosaic -- Made Possible in Part by Optical Navigation

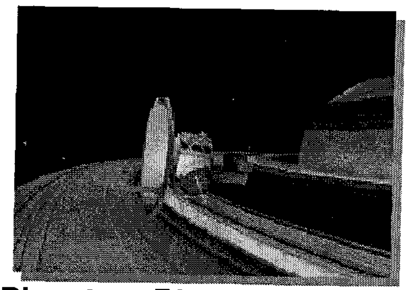
allowing high-resolution science frames near satellite encounters such as this to become possible...

Without optical navigation, Voyager mission would have returned only on order of 10% of high-resolution science that it did return

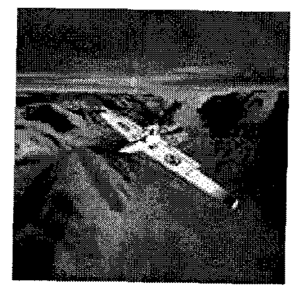
Navigation Challenges -- Extension of Capabilities

- For several classes of new missions, shape and topography of target are unknown and/or changing rapidly
  - Surface and sub-surface navigation on Europa
  - Precision landing on comets and asteroids
  - Navigating near rings of Saturn
  - Aircraft navigation at Mars
- Also, many future missions require navigation updates on order of seconds (or faster), and thus, cannot be done via Earth:
  - Aerocapture
  - Precision landing
  - Rendezvous and docking
  - Rapid in-situ navigation

Sub-surface Navigation

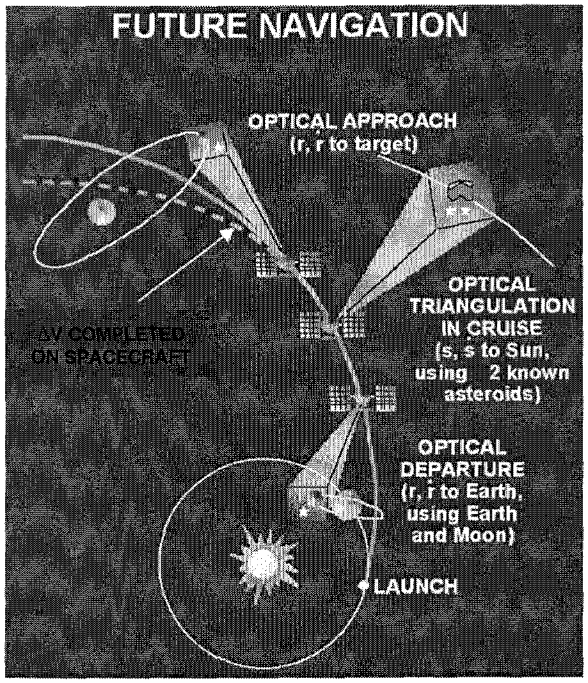


Planetary Ring Navigation



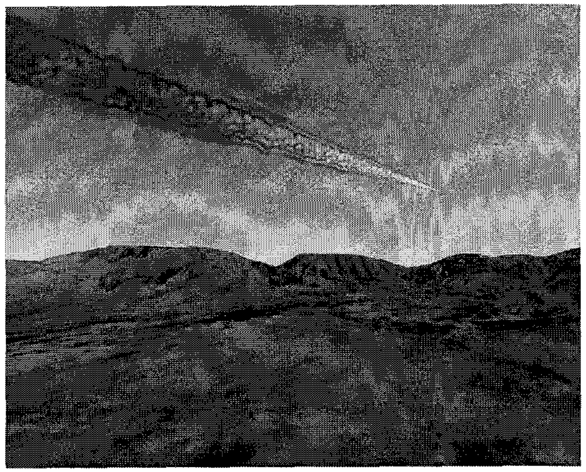
Mars Aircraft Navigation

New Mission Scenarios That Pose Navigation Challenges



Autonomous Navigation

Interplanetary cruise, flybys, and orbiter scenarios for all missions



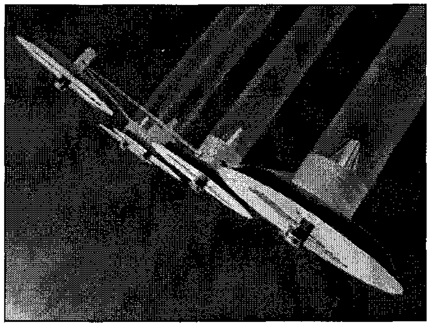
Aerocapture

Missions going into orbit about Venus, Mars, Saturn, Uranus, Neptune

Precision Landing

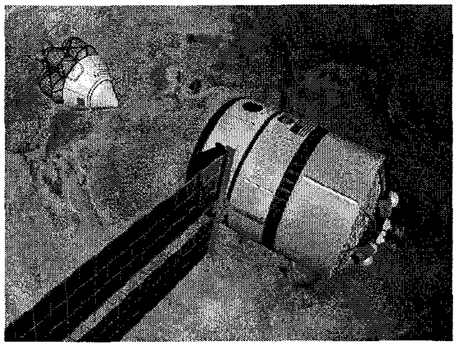
Landing on or hovering near small bodies, terrestrial bodies, or planetary satellites

New Mission Scenarios That Pose Navigation Challenges (Continued)



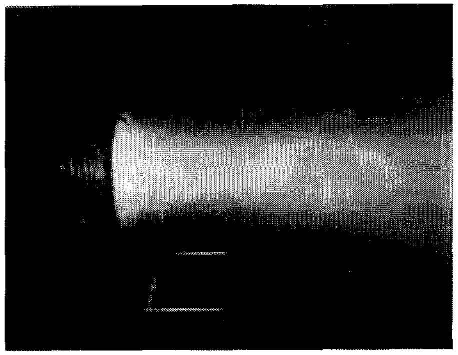
<u>Multi-Vehicle GN&C</u>

Mars constellations, formation flying, etc.



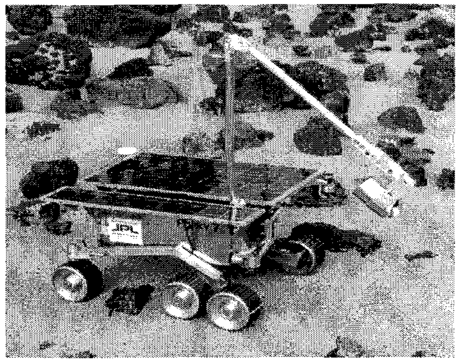
<u>Rendezvous & Docking</u>

Sample return missions to terrestrial planets, small bodies, and planetary satellites



<u>Low-Thrust Guidance & Navigation</u>

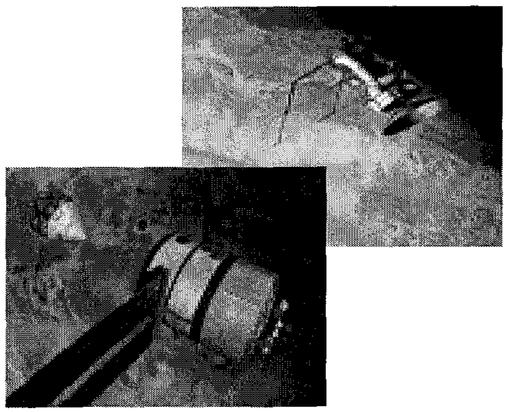
Mercury, small body, and outer planet missions



<u>*In-Situ* Vehicle GN&C</u>

Rovers, balloons, submarines, and aircraft, on planets, satellites, and small bodies

Deep Space Navigation Roadmap

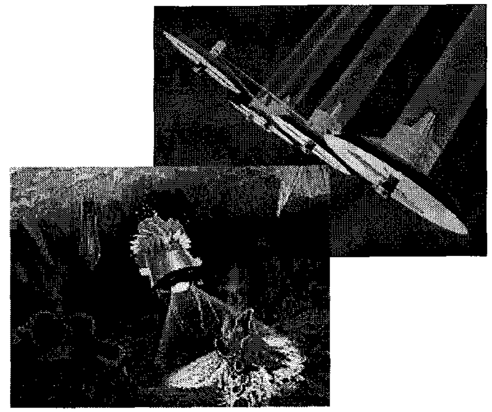


Deep Space Navigation Autonomy
Autonomous Rendezvous and Docking
Aerocapture

Mars '03 -'05
Europa Orbiter
Pluto/Kuiper Express
Deep Impact

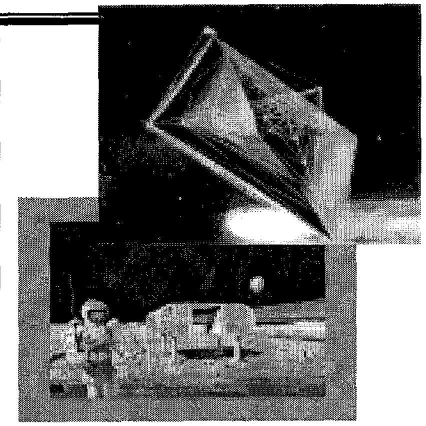
Precision Landing
Multi-Vehicle GN&C
Low-Thrust GN&C
In Situ Vehicle GN&C

Venus Sample Return
Mars Networks
Europa Lander
Neptune / Triton Orbiter
Titan Organics Explorer
Comet Nucleus Sample Return
Terrestrial Planet Finder



Autonomous *In Situ* GN&C
In-Orbit Hazard Avoidance
Small Body Modeling
Advanced Formation GN&C

Mars Robotic Outposts
Deep Atmospheric Probes
Saturn Ring Observer
Satellite Robotic Outposts
Asteroid Sample Return
Terrestrial Planet Imager



Advanced *In Situ* GN&C
Solar-Sail Navigation

Permanent Colonies
Satellite Sample Return
Interstellar Precursors

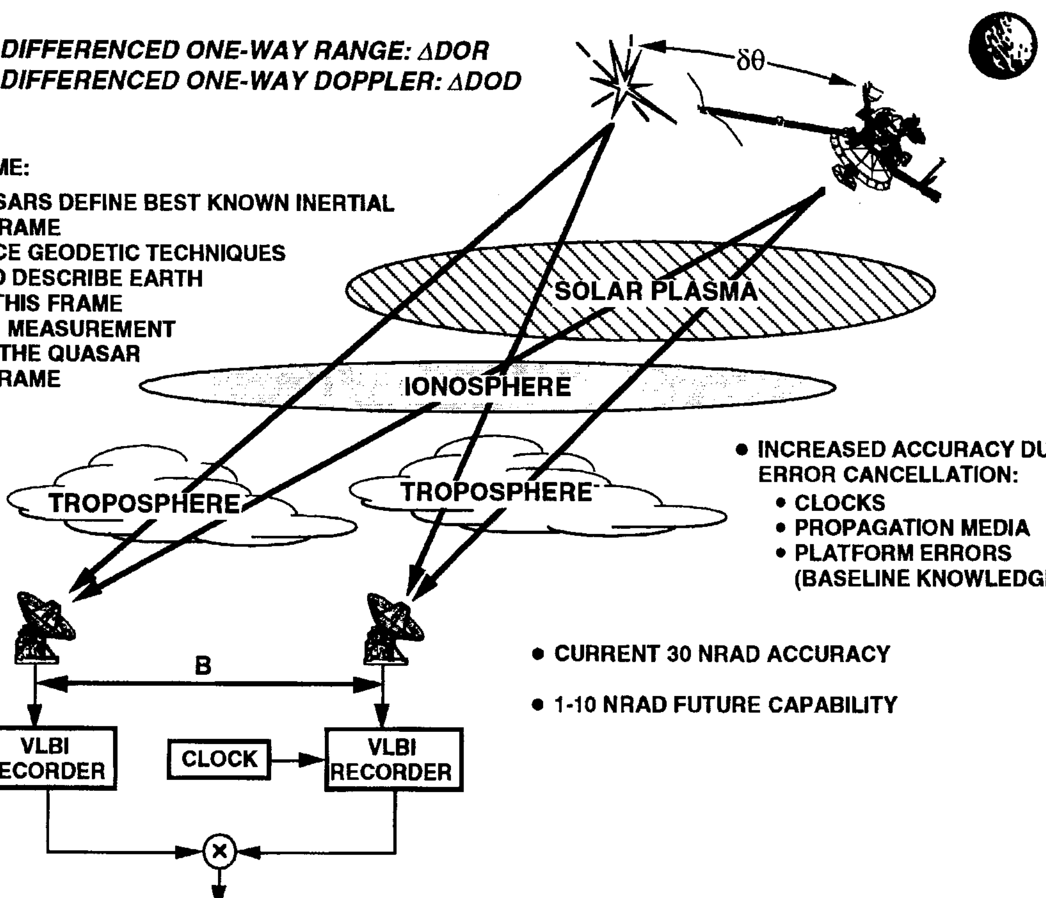
Timeline 2000 2005 2010 2015 2020 2025

Navigation to all regions of the solar system and beyond

Spacecraft-Quasar Differential Angular Techniques

- *Δ VLBI*
  - *DELTA-DIFFERENCED ONE-WAY RANGE: ΔDOR*
  - *DELTA-DIFFERENCED ONE-WAY DOPPLER: ΔDOD*

- REFERENCE FRAME:
  - DISTANT QUASARS DEFINE BEST KNOWN INERTIAL REFERENCE FRAME
  - MODERN SPACE GEODETIC TECHNIQUES MEASURE AND DESCRIBE EARTH ROTATION IN THIS FRAME
  - DIFFERENTIAL MEASUREMENT TIES S/C INTO THE QUASAR REFERENCE FRAME



- INCREASED ACCURACY DUE TO ERROR CANCELLATION:
  - CLOCKS
  - PROPAGATION MEDIA
  - PLATFORM ERRORS (BASELINE KNOWLEDGE)

- CURRENT 30 NRAD ACCURACY

- 1-10 NRAD FUTURE CAPABILITY

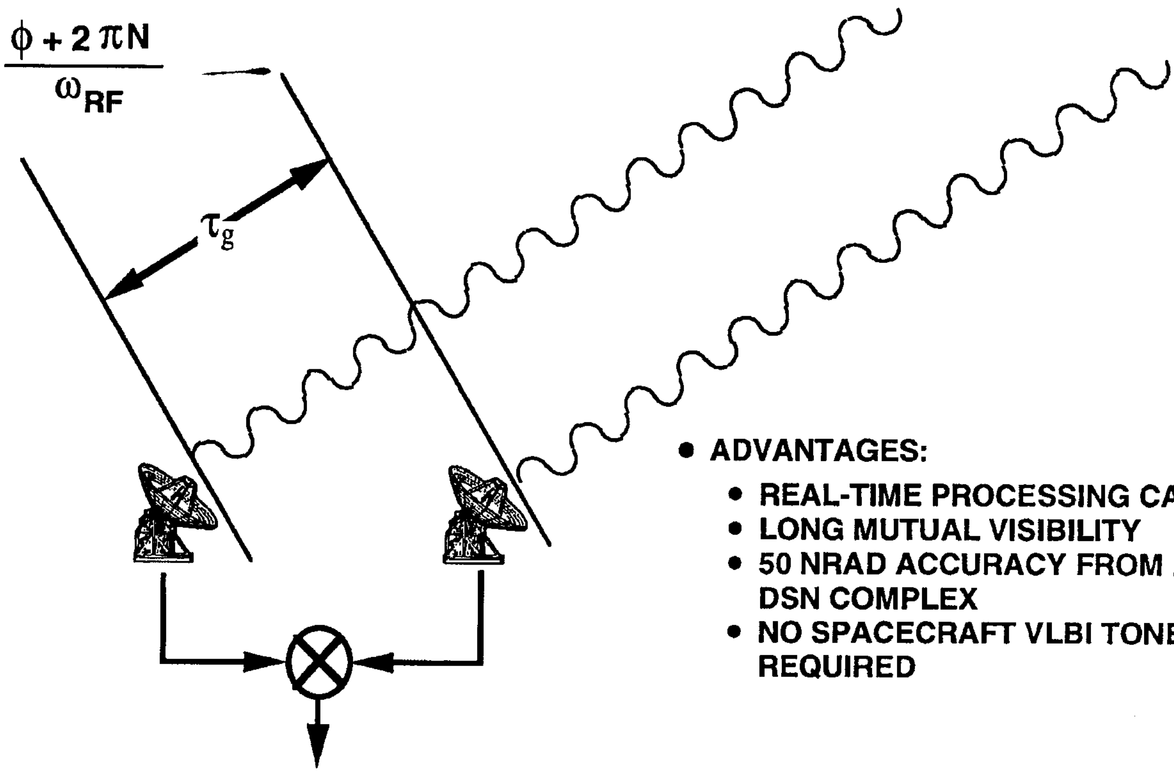
$$\Delta\rho_{s/c} = B \cos\theta_{s/c} + c\,(\Delta\tau_{clock} + \Delta\tau_{inst} + \Delta\tau_{media}) + \text{NOISE}$$

$$\Delta\rho_{Q} = B \cos\theta_{Q} + c\,(\Delta\tau_{clock} + \Delta\tau_{inst} + \Delta\tau_{media}) + \text{NOISE}$$

Connected Element Interferometry

- *CONNECTED ELEMENT INTERFEROMETRY (CEI):*
  - ON SHORT BASELINES, THE INTERFEROMETRIC PHASE OBSERVABLE CAN BE USED DIRECTLY TO OBTAIN AN EXTREMELY PRECISE MEASURE OF GEOMETRIC DELAY

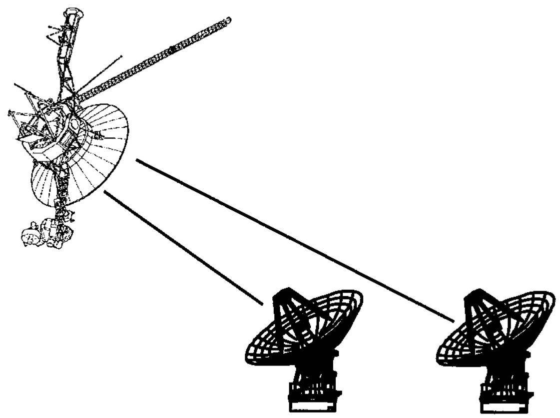
$$\tau_g = \frac{\phi + 2\pi N}{\omega_{RF}}$$



$$\phi = \omega_{RF}\,\tau_g$$

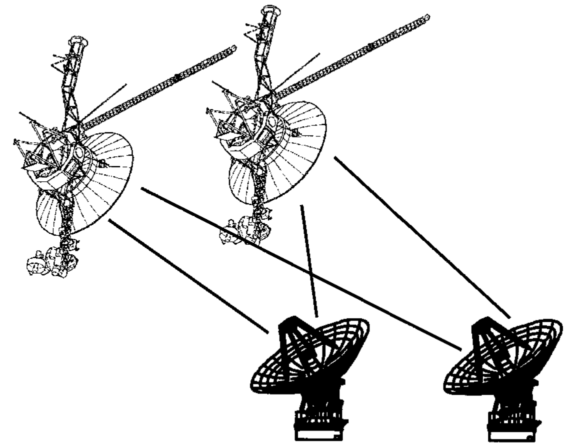
- ADVANTAGES:
  - REAL-TIME PROCESSING CAPABILITY
  - LONG MUTUAL VISIBILITY
  - 50 NRAD ACCURACY FROM A SINGLE DSN COMPLEX
  - NO SPACECRAFT VLBI TONES REQUIRED

Radio Metric Measurements -- Quasi-Interferometric Data Types (Spacecraft Signals Only)



- Differenced Doppler
  - Measurements are difference in Doppler measurements at two different stations
  - Most useful during planetary approach and for planetary orbiters
  - Used in Magellan and Galileo missions

- Differenced Range
  - Measurements are difference in arrival times of spacecraft downlink signal at two different stations
  - Most useful during planetary approach and for outer planet orbiters
  - Used in Voyager mission



- Spacecraft-Spacecraft ΔDOR
  - "Differenced" differenced range, using signal cross-correlation to obtain group delay of signals arriving at two stations
  - Used to obtain angular information; useful if one spacecraft is planetary orbiter and second is nearing that planet
  - Applications are planetary approach navigation and planetary rover navigation

Radio Metric Orbit Determination for Planetary Orbiter

- Doppler tracking of spacecraft in orbit about another planet does not determine all orbital elements equally well
  - Longitude of ascending node in plane-of-sky coordinate system difficult to determine
  - Inclination in plane-of-sky coordinate system difficult to determine when near 90°
  - All elements except inclination difficult to determine when plane-of-sky inclination near 0° or 180°
  - Number of poor geometries and degree of severity increase as orbit eccentricity approaches zero
- Multi-station differenced-Doppler data (or functional equivalent) can be used to measure one or more plane-of-sky velocity components and resolve indeterminacies associated with single-station Doppler data